Review: effects of wind on trees

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Abstract: Wind not only causes extensive damages to trees in many parts of the world, it also has more subtle effects on the growth and morphology of trees and forest ecology as well. Wind damage to trees has historically been the field of silviculture, but increasing recognition of the importance and complexity of the subject has recently got people involved from many other disciplines. Due to the global climate changes, it is believed that the risk of further and stronger storms is increasing. In order to better understand the effects of wind on individual trees, forest stand and forest ecosystem, and further to practice the management of forests, it is necessary to summarize the research results related to this subject. This review was mostly based on the references from recent researches in the field, especially from the symposium volumes of some international conferences on this subject. The results indicated that there have been significant progresses in the following aspects: 1) the aerodynamic interaction between wind and trees, 2) the mechanics of trees under wind loading and adaptive growth, 3) the tree's physiological responses to wind, and 4) the risk assessment of wind damage to forest. However, there are some aspects which may need further studies: 1) wind damage to natural forests, 2) wind-driven gap formation and forest dynamics, 3) the effects of changes resulted from wind disturbances on ecological processes of forest ecosystem, and 4) management for the wind-damaged forests.

Key words: Wind; Wind effect; Trees/forest; Forest ecology; Disturbance

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Introduction

Wind moves in both horizontal and vertical directions, being affected by the conditions of surfaces it encounters (Hannah *et al*, 1995). Generally, surface wind extends from 50 to 100 m above the earth's surface and dominated by strong mixing, i.e., turbulence (Kimmins 1987; Takeuchi 1997). The surface wind influences the habitats of wildlife, the growth of crop and livestock, soil erosion, snow distribution, sand blowing, etc.. Strong wind causes extreme damages, especially in the sandy areas with arid, semi-arid climates. Wind has long been regarded as an important ecological factor in forests, for it transports water vapor, heat energy, pollen grains, spores, and seeds of plants, generates static electricity, and affects evaporation and transpiration. The strong/extreme wind can erode soil, do severe damages to farms (Jiang and Zhu 1993a, b; Coutts and Grace 1995), trees and forests (uprooting, breakage, crown damage), and further more, even destroy forest or change the composition of forest communities (Odum 1983; Ennos 1997). The long-term wind regime of a site also makes very strong influences on many aspects of tree growth, morphology, physiological processes, and forest ecology (Kimmins 1987; Ennos 1997). Damages to forests by wind is a significant problem in boreal temperate and mountain forests (Nykänen *et al.* 1997; Valinger and Fridman 1997; Peltola *et al.* 2000; Schönenberger 2002), which not only leads to timber losses through reducing the timber quality and quantity, but also leads to disturbances to the ecological conditions of forest ecosystem, and influences the ecological service functions of forest as well.

In order to obtain the improved knowledge about the interaction of wind flow and forests, to better understand the physics of storm catastrophes, to make the definition of effective counter measures, to minimize the damages, and to find a better way for pre-and-post damage management, three international conferences were held under the auspices of IUFRO (International Union of Forestry Research Organizations) in the recent decade. The first international conference was held in July of 1993 at Heriot-Watt University, Edingburgh, Scotland, followed by a publication of WIND AND TREES (Coutts and Grace 1995) with 27 papers. The second conference was held in September 1998 at University of Joensuu, Joensuu, Finland, and 30 selected papers were published in a special issue of Forest Ecology and Management (2000, Vol. 135, No. 1-3), with its focus on WIND AND OTHER ABIOTIC RISKS TO FORESTS (Peltola *et al.* 2000). The third conference was held in September of 2003 at University of Karlsruhe, Karlsruhe, Germany. A symposium volume of WIND EFFECTS ON

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TREES was published, which contained a selection of 52 papers (Ruck *et al.* 2003). These conferences have positively affected the understanding of the main processes involved. However, due to the global climate changes, it is believed that the risk of further and stronger storms is increasing. For better understanding the relationships between wind and forest damage, the effects of wind on individual trees, forest stand and forest ecosystem, and practice of forest management, it is necessary to summarize the research results related to this subject. This review is mostly based on the symposium publications from the three international conferences.

Ecological effects of wind on trees

Influence on photosynthesis

Wind has significant effects on the exchange of air between plants and the surround environment, e.g., when the airflow blows through the trees, the leaves are moving in the wind, thus, the air is pumped in and out of the leaf spaces through the stomata of the leaves, which accelerates the exchange of CO_2 and O_2 (Kimmins 1987; Zhu *et al.* 2000a). Leaf surface temperatures, leaf shape and leaf transpiration rates are also influenced by wind speed (Grace 1988; Ennos 1997; Smith and Jarvis 1998). The reduction by wind in the thickness of the boundary layer of humid air around leaves accelerates the diffusion of water vapor out through the stomata. This increases the evaporation even when the vapor pressure deficit is zero, because of the important effect of convection on evaporation (Telewski 1995). However, Grace (1988) came out with a contrary conclusion that when leaves are brightly illuminated, an increase in wind speed often causes a decline in transpiration rate. This is because that if the wind speed increases, the aerodynamic resistance declines and the leaf temperature fall close to air temperature. As the vapor pressure by water in the sub-stomatal cavities is a strong function of temperature, the driving gradient for transpiration will inevitably fall. Generally, the short run effects of wind on photosynthesis are complex and often hard to predict (Telewski 1995; Ennos 1997). Gentle breeze usually increases the photosynthesis, because that the low wind speed reduces the thickness of the boundary layer, thus, the resistance to movement of CO_2 will fall. The strong wind may reduce photosynthesis because of its direct and indirect effects, meaning that strong wind cools and curve up the leaves, which reduces the effective area of leaves. At the same time, the leaf stomata close to reduce water loss. This increases the resistance to the entry of CO_2 (Telewski 1995). Wind speed affects the air exchange, air shape, temperature and vapor of leaves. Therefore, the physiological processes (photosynthesis) are affected by wind.

The influence of wind on tree growth and development is interpreted within the context of stress and strain relationships (Telewski 1995). The physiological responses of tree to wind have been studied through leaves and in relation to the growth of woody tissues. Foliar studies have focused on heat transfer, transpiration, photosynthesis, desiccation and leaf growth and expansion. The interactions between the different responses and stresses associated with wind are outlined through foliar and vascular tissues (Fig. 1). The influence of wind on tree growth and development is very complex. It is doubtful that if any one stimulus can explain all the observed responses (Telewski 1995). Therefore, more detailed researches on this subject for individual tree species are needed.

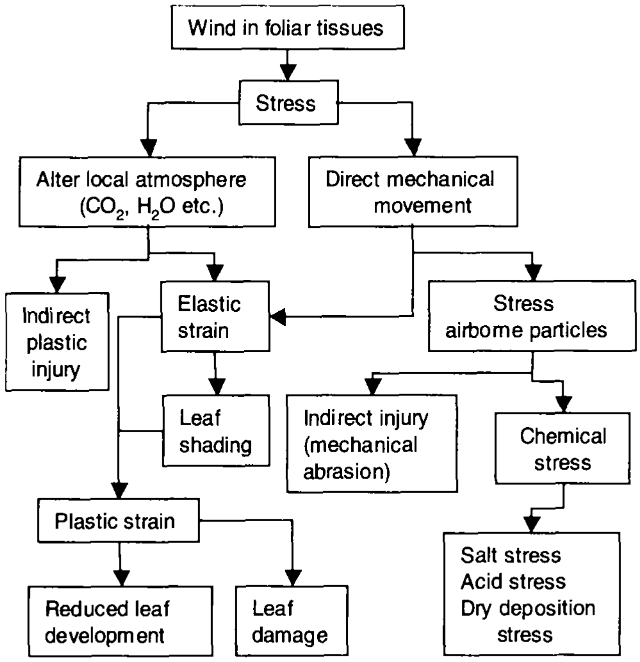

Fig. 1 Stress, strain and injury induced by wind in foliar tissues (Quoted from Telewski 1995).

Acclimatization to environment

There is no doubt that trees show the acclimation to their local wind environment. The wide range of much longer-term acclimatory changes in the development process in strong wind seems to increase the tree stability. Wind-exposed needles often contain higher proportion of collenchyma (A supportive tissue of plants, consisting of elongated living cells with unevenly thickened walls) and sclerenchyma (A supportive plant tissue that consists of thick-walled, usually lignified cells) tissues, which make the needles stiffer and tougher. Therefore, the wind-exposed trees increase their resistance to both frost and herbivore (Ennos 1997). The oscillations of trees induced by wind make the trees reduce the elongation growth and increase the radial growth of both trunk and branches, as the trees tend to acclimate the wind conditions through reducing the mechanical stresses and the over turning moment. Therefore, the trees growing in strong wind are of high taper ($D_{1.3}$/H, $D_{1.3}$: diameter at breast height, 1.3 m, H: tree height) (Peltola *et al.* 1993; Peltola 1996). Stem tensions that result from the swaying of trees produce another adaptation of

tree buttress. Tree ring growth is accelerated in the angles between the lower stem and the larger roots, which results in the formation of large stem buttresses (Kimmins 1987), especially at the positions on the trunk that give the tree most support against the prevailing winds (Gardiner and Quine 2000).

Changes of tree morphology

Wind is very important in determining the phenotypic appearance of trees. Wind affects the morphology of root, stem and crown through influencing the distribution of growth. The most common phenomenon is the flag-shaped crown of coniferous trees. It is usually caused by wind-blown sand, which removes the bark of trees, especially in the shore sand dune areas. Take another example, the wind abrasion of Japanese black pine (*Pinus thunbergii* Parl.) in a coastal forest, where the wind-blown ice crystals killed the foliage and buds of trees in the early spring (Fig. 2A). However, the foliage and buds of trees in the lee wind are less influenced.

Fig. 2 Morphological changes of Japanese black pine (*Pinus thunbergii* Parl.) in the coastal forest belt of Japan Sea caused by windblown sand. (A) Blown-sand, salt wind kills the buds of trees on the windward side, (B) tree slanting caused by chronic winds (Quoted from Zhu *et al.* 2004).

The trees become dwarfed if they are exposed to frequent dry wind, as the cells receive insufficient water to expand to the normal size in the sheltered locations. The effects of wind on tree morphology sometimes result from materials carried by wind rather than from wind itself (Kimmins 1987; Zhu *et al.* 2002b). This may be the result of physiological desiccation, toxic effects of salt or physical abrasion caused by the wind-driven particles (Kimmins 1987). Tree leaves exposed to wind become thicker and smaller, and have a lower rate of water loss per unit area than the leaves growing in sheltered situations. The rings of tree stem always respond to wind. For example, the bending forces of chronic wind in Japanese black pine (*Pinus thunbergii* Parl.) resulted in the development of enlarged annual rings of compression wood on the leeward side (Fig. 2B), and reduction or even elimination of some annual rings on the windward side of the stem. According to Zhu *et al.* (2000b), the slanting direction and degree of trees exposed to wind are not influenced by the most frequent wind, but by the wind, which blows in the growth season (Fig. 3).

Effects of wind on forest ecosystem

The effects of wind mentioned above are generally the results of the chronic, moderate wind speed. Although wind can alter forest ecosystem in many ways, e.g., the transport of pathogens and insects by wind in forest ecosystem can lead to the destruction of dominant tree species, the fast and direct effects of wind on forest ecosystem may be the dramatic wind events, such as hurricanes or storms, which can alter forest ecology by destroying trees rather than changing the distribution of tree growth. There are many studies about the damages by wind (Valinger *et al.* 1993; Everham III 1995; Foster and Boose 1995; Gardiner 1995; Quine 1995; Peltola *et al.* 1997, 1999; Zhu *et al.* 2002a), which demonstrated that storm could damage and kill both climax and pioneer trees. Recovery of forest after such storms involves re-sprout of the damaged tree species, and the massive growth of seedlings of pioneer species (Ennos 1997). The survival and forest regeneration already established on storm-impacted sites can explain in large part the very rapid recovery of biotic control of the ecosystem processes (Foster and Boose 1995). Based on the effects of windstorm in this way, it can be concluded in some extent that storm may reverse the processes of succession for the forest ecosystem. Recently, the study of storm meteorology presents the potential to relate the storm damage to forest ecosystem dynamics and spatial patterns at landscape to regional scale (Foster and Boose 1995; Peterson 2000; Wichmann and Ravn 2001). Additionally, much literature related to wind-throw gap and patch formation in natural and managed forests describe studies in response to discrete events causing substantial changes. There are more frequent wind damages or wind-disturbances observed in some regions (Quine 2003). Therefore, the expansion of existing gaps is regarded as an important component of endemic wind-throw. But an emphasis on monitoring of the

whole forests, and the imprecision of geo-referencing in the photographic interpretation process has prevented this being confirmed (Quine 2003).

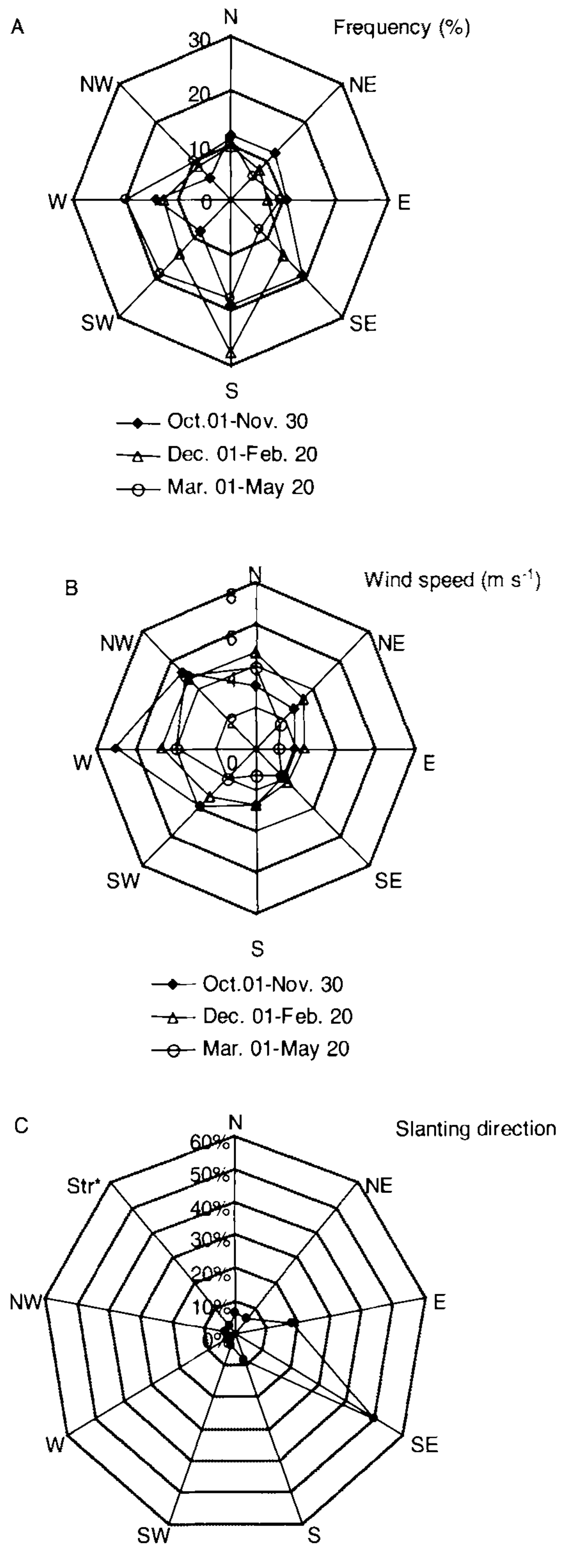

Fig. 3 Relationship between wind frequency, wind magnitude and frequency of tree slanting. (A) Distribution of wind direction, (B) corresponding mean wind speed, and (C) the distribution of slanting trees. Str* means the stem is straight.

Generally, the characteristics of individual gaps have attracted less attention than measurements of the proportion of wind-throw formation within the stand or management unit.

Wind damages to forests

Any forest damages caused by meteorological phenomena might be usual/normal in a long-term history for a forest ecosystem, but it might be unusual/abnormal to the owners who stand on the view-point that the human life time should be adopted as the unit time to the consideration (Harley 1968; Matsuzaki 1994; Zhu *et al.* 2004). The influence of wind on forestry (forest management and planning) can be considered at two main stages in the life of the forests, particularly for the plantation forests. The first stage is at the time of planting. The second is the time when dealing with the established forest, in particular with thinning and regeneration (Godwin 1968). Obviously, influence of wind on the latter, forest management, has been paid great emphasis. Therefore, the problem of tree or stand stability against wind damages has received more attentions in recent decades (Hutte 1968; Stumbles 1968; Petty and Worrell 1981; Cremer *et al.* 1982; Petty and Swain 1985; Galinski 1989; Peltola and Kellamaki 1993; Quine 1995; Gardiner *et al.* 1997; Peltola *et al.* 1999; Moore and Quine 2000, Zhu *et al.* 2002a, 2003a).

Aerodynamic interaction between wind and trees

Strong winds associated with Atlantic depressions in Northern Europe, hurricanes in North America and cyclones in New Zealand, Japan and the Pacific Islands, cause extensive damages to forests. Considerable research has been conducted to understand the physical processes involved in order to improve silvicultural practices and to predict better the likelihood of damages (Gardiner 1995). Researches indicate that the trees can be blown down at wind speeds considerably lower than those predicted from static pulling experiments under calm conditions (Oliver and Mayhead 1974; Blackburn and Petty, 1988). Generally, the explanation is that trees are dynamic structures capable of resonating at their natural sway frequency with the turbulent wind field, and this explanation has been explored theoretically and in field measurements of tree movement and turbulence characteristics (Gardiner 1994; Zhu *et al* 2002c, d).

The link between the wind speed and the force on a tree is made by defining a drag coefficient (C_d).

$$C_d = \frac{2D}{\rho U_c^2 H} \tag{1}$$

where D is drag force (N), ρ is air density (kg m^{-3}), U_c is reference wind velocity (m s^{-1}), which is usually replaced by U_H, the wind speed at H (Cao 1983).

Research shows that drag force D can be obtained according to wind speed by exponential function (Wood 1995). Another way to assess the mean drag forces on trees is to measure the Reynolds shear stress in the flow above the canopy, the wind above the forest canopy has mean velocity components U parallel to the ground and W vertically upward, together with superimposed fluctuation components of u, v, w in streamwise, lateral and vertical directions, respectively. The product of ρ $(W+w)$ describes an instantaneous upward mass flow per unit area. When ρ $(W+w)$ is multiplied by streamwise velocity $(U+u)$, the upward flux of streamwise momentum per unit area can be obtained (Wood 1995). The mean forces may express the Reynolds shear stresses, but they are little practical importance when extremes of the fluctuating forces are much larger. The mechanism of Reynolds shear stress explains physically how fluid transferred downward (penetration) by negative w gust components will frequently carry an excess of horizontal u velocity. The gust penetration events have been observed in the field and in the wind tunnel (Gardiner 1995; Gardiner *et al.* 1997; Zhu *et al.* 2002d; Lohou *et al.* 2003), which called HONAMI gusts.

Gardiner's (1995) results indicate that the movement of trees has been correlated to two turbulence parameters, i.e., $u'w'$ (the momentum flux) and u_r' (the variation in rotated velocity), which can be used as indictors of the passage of coherent gusts. Although the trees respond well to frequencies close to their resonant frequency, their behavior is closer to that of damped harmonic oscillators, subject to intermittent impulsive loading (Gardiner 1995).

Wind damage to forest

Wind damage is one of the major constraints in silvicultural practice (Blackburn and Petty 1988; Mayer 1989; Rollinson 1989; Zhu *et al.* 2003a). Most studies on wind damages to forest are concerned in the timber-production forests. Catastrophic wind events, such as cyclonic storms, gales and tornadoes, influence the forests all over the world. The global climate change models predict an increase in both frequency and intensity of these types of storms events (Everham III 1995; Schönenberger 2002). Generally, species differences, stand age, size, silvicultural treatments (even-aged stands, thinning regime, exotic species introduction), topographic features and frequency of the previous wind disturbance all influence the intensity and the spatial pattern of damages. These disturbance events have been observed and quantified for over a century, but few clear generalizations have been drawn about their impacts (Everham III 1995). Wind damage can be mainly classified as stem damage and canopy damage. The most commonly reported one is stem damage, which includes uprooting, breakage, and bending or leaning. Canopy damage may be quantified directly on the basis of branch loss and canopy defoliation. Canopy damage can be indirectly determined using the techniques to measure structure or changes in light level, and the branch damage is quantified either by counting branches damaged or by assignment to arbitrarily defined categories. The researches on wind damage have produced the following conclusions (quoted by Everham III 1995).

1) Variation in stem breakage as opposed to uprooting varied between forests sometimes correlated to stem size.

2) Larger size trees are more likely to be directly damaged by wind. The small trees or understory trees are more susceptible to indirect damage from other trees falling on them.

3) Previous mechanical damage to trees increases subsequent wind damage.

4) Generally low levels of mortality, but high structural damage.

But following relationships are unclear:

1) Relationship between damage of conifers versus broadleaved trees.

2) Standardization to examine the wind damage among different forests, with different trees, in different positions on the landscape or the globe.

3) Correlation between topographic exposure and intensity of damage.

Risk assessment of wind damage to forest

The risk of wind damage is subject to very complex factors associated with the stature of trees, the aerodynamic properties of stand, the general and local incidence of winds, soil conditions, and so on. These factors can be classified into three main aspects, i.e., weather, site and stand conditions (Cremer *et al.* 1982). The weather conditions are always beyond human control (Matsuzaki 1994). The site conditions are mainly permanent for a specific location, while the stand conditions are the most important and controllable. The features of stand are subject to changes with growth and silvicultural measures. Foresters have used the ratio of $H/D_{1.3}$ or taper $D_{1.3}/H$ as a measure of risk of wind damages. The ratio of $H/D_{1.3}$ is considered as the most important factor likely to influence the stability of stand (Petty and Worrell 1981; Cremer *et al.* 1982; Blackburn and Petty 1988). The ratio of $H/D_{1.3}$ can be calculated in several ways, but mostly from the mean height and diameter of all the trees in the stand. However, Cremer *et al.* (1982) suggested that both tree height (H) and stem diameter ($D_{1.3}$) calculated from the mean values of the largest 200 stems per hectare, i.e., H_{200L}/D_{200L} (where H_{200L} and D_{200L} were the mean tree height and mean $D_{1.3}$ of the largest 200 stems per hectare) could be considered as a valuable index for the risk of wind damage. This is because the smaller trees are far less significant than the dominant trees in determining the stability of the stand, and selectively removing the smaller trees by thinning will at once boost the ratio of $D_{1.3}/H$, and thus wrongly suggested that the risk was lowered.

The other ratios of height and diameter are also used as

the alternative indexes of $H/D_{1.3}$, such as $H/D_{1.3}^3$, $H/D_{1.3}^2$ and $H^{3/2}/D_{1.3}$. Generally, $H/D_{1.3}^3$ relates to the strength of a cantilever of uniform resistance (Gardiner *et al.* 1997). $H/D_{1.3}^2$ is closely related to the shape of stem (Cremer *et al.*, 1982), and $H^{3/2}/D_{1.3}$ gives the greatest relative weight to tree height and relates best to elastic strength properties (Valinger *et al.* 1993).

The relationship between the index values and incidence of wind damage showed that the combination of height and diameter in $H/D_{1.3}$ value was valuable for providing the first indication. However, risk of wind damage depends not only on the sturdiness of the tree population, but also on the aerodynamic properties of the stand, as well as on wind conditions. Therefore, the relationship between the above mentioned index values and incidence of wind damage could only provide a broad indication of risk. Blackburn and Petty (1988), and Galinski (1989) suggested a practical method for evaluating the risk of wind damage from the combination of stem bending theory and wind regime. Based on the fundamentals of the method, Zhu *et al.* (2002a, 2003a) developed the models to estimate the risk of wind damage for a single tree (Equations 2) and a stand (Equations 3), respectively.

$$R(s) = \frac{\sum H_i \exp[(\alpha_b - \alpha_s)(1 - \frac{H_i}{H})]}{D_{1.3}^3 \pi} \tag{2}$$

Where *R(s)* is the risk ratio of a single tree, H_i is thecon-cerned height within the crown of a single tree (m). H is the top height of tree crown (m). α_s is a constant, which determines the form of the wind profile within the singletree crown (Zhu *et al.* 2000a). α_b is the coefficient related to total length of needled branch. $D_{1.3}$ is the stem diameter at breast height (cm).

Equation (2) allows a comparison of growth strategies among individual trees, where the higher the *R(s)*, the higher the probability that the considered tree will be destroyed during the strong wind period.

$$R(t) = \frac{\int_h^H z \exp[-(2\alpha + v)(1 - \frac{z}{H})] dz}{D_{1.3}^3} \tag{3}$$

Where *R(t)* is the risk ratio of a stand. v is the extinction coefficient of distribution of optical stratification porosity (Zhu *et al.* 2003b). α is a constant, which determines the form of the wind profile within the stand.

$D_{1.3}$ in Equation (3) is the mean diameter of the stand calculated from various sample patterns (mean $D_{1.3}$ of all stems, mean $D_{1.3}$ calculated from the mean values of the 200 largest stems per hectare and so on). Risk ratio estimation of *R(t)* allows a comparison of growth strategies among different stands. The bigger the R (t), the higher the probability that the considered stand will be destroyed by the strong wind.

Management responses to wind

How wind blowing in forest stands and in their boundary regions concerns the forest manager in a number of important ways, in particular, of thinning and regeneration (Godwin 1968; Slodičák 1995).

The wind flow over unbroken forest in flat terrain is approximately laminar, but it may become turbulent as the wind passes into broken or clearcut areas. Turbulence often develops along the windward edge of a clearcut, which can result in windblown or other wind damages. However, turbulence is not usually the major cause of tree or forest damage on clreacuts. From the clearcut area the wind usally accelerates and then leaves (Kimmins 1987). As wind passes over the leading edge of a clearcut area, the wind falls from the canopy onto the ground. To leave the clearcut area, the wind must regain its original height by rising up over the uncut stand at the downwind end of the clearcut area. This involves acceleration of the wind, which depends on the shape of the clearcut. The increased velocity of wind may increase its kinetic energy. Some of the energy is transferred to the trees as the wind leaves the area. This can result in windblown or wind damage to trees. Generally, windblown is far more common in stands adjacent to clearcut areas than in stands well away from clearcut. Trees in a fully stocked stand provide each other with mutual shelter, and only the uppermost part of the crowns of the largest trees experiences the full force of the wind. However, much more complicated situations of forest damage occur in the practice of forest management.

Summary

The current research results about wind and trees have proved to be readily applicable to forestry (Ennos 1997). For example, forest managers are now using the knowledge of response of trees to wind in thinning a plantation stand. Wind not only causes extensive damages to trees in many parts of the world, also has more subtle effects on tree growth, tree morphology, and forest ecology as well. Wind damage to trees has historically been the field of silviculture, but increasing recognition of the importance and complexity of the subject has more recently involved people from many other disciplines. Therefore, many studies should also help foresters and ecologists to shed more light on the natural forests. The three international conferences on the subject of wind and trees have greatly assisted the understanding of the main processes involved. Especially, the aspects of aerodynamic interaction of wind and trees, mechanics of trees under wind loading and adaptive growth, tree physiological responses to wind and risk assessment of wind damage for forest have been achieved significant advances. However, most of the studies have been carried out in plantations in Europe. It is necessary to conduct the related research in other continents. In addition, the following aspects in this subject may

need more researches: 1) wind damage to natural forests, 2) wind-driven gap formation and forest dynamics, 3) the effects of changes resulted from wind disturbances on ecological processes of forest ecosystem, and 4) management for wind-damaged forest.

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